

# Sewer Gas: An Indoor Air Source of PCE to Consider During Vapor Intrusion Investigations

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## Abstract

The United States Environmental Protection Agency (USEPA) is finalizing its vapor intrusion guidelines. One of the important issues related to vapor intrusion is background concentrations of volatile organic compounds (VOCs) in indoor air, typically attributed to consumer products and building materials. Background concentrations can exist even in the absence of vapor intrusion and are an important consideration when conducting site assessments. In addition, the development of accurate conceptual models that depict pathways for vapor entry into buildings is important during vapor intrusion site assessments. Sewer gas, either as a contributor to background concentrations or as part of the site conceptual model, is not routinely evaluated during vapor intrusion site assessments. The research described herein identifies an instance where vapors emanating directly from a sanitary sewer pipe within a residence were determined to be a source of tetrachloroethylene (PCE) detected in indoor air. Concentrations of PCE in the bathroom range from 2.1 to 190  $\mu\text{g}/\text{m}^3$  and exceed typical indoor air concentrations by orders of magnitude resulting in human health risk classified as an "Imminent Hazard" condition. The results suggest that infiltration of sewer gas resulted in PCE concentrations in indoor air that were nearly two orders of magnitude higher as compared to when infiltration of sewer gas was not known to be occurring. This previously understudied pathway whereby sewers serve as sources of PCE (and potentially other VOC) vapors is highlighted. Implications for vapor intrusion investigations are also discussed.

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## Introduction

Vapor intrusion involves the migration of contaminated vapors from soil and groundwater into indoor air spaces. The problem of vapor intrusion has been studied for decades, beginning with radon in the 1970s. Vapor intrusion of volatile organic compounds (VOCs) has been gaining attention among risk assessors and the regulatory community since the early 1990s (McAlary and Johnson 2009). Today, the VOC vapor intrusion pathway is included as part of nearly all hazardous waste site human health risk assessments.

In most risk assessment scenarios, the preferred method for assessing risks is to sample the media to which a receptor is exposed. In the case of vapor intrusion, where the main exposure pathway is inhalation of contaminated indoor air, the medium sampled is indoor air. Sampling indoor air may establish the magnitude of the health risk, but it does not provide information about the source of the contamination. For instance, in-home VOC sources can result in elevated indoor air concentrations in the absence and/or presence of vapor intrusion. Therefore, vapor intrusion investigations will also collect environmental samples to more accurately determine the source of indoor air VOCs. The nature and location of sampling is often driven by the site conceptual model, which identifies the various pathways for vapors to enter a building.

In the context of assessing vapor intrusion, background (i.e., "typical indoor air") concentrations describe the contribution of in-home sources to measured indoor air concentrations in buildings where vapor intrusion is not expected to be occurring. A number of indoor air studies attempting to characterize background levels of VOCs have been included in compilations (Shah and Singh 1988; Stolwijk 1990; Brown et al. 1994; Holcomb and Seabrook 1995; USEPA 1998, 2011; Hodgson and Levin 2003). The most recent and relevant of these compilations is the United States Environmental Protection Agency's (USEPA's) technical document on background indoor air concentrations of VOCs in North America (2011), which reviews data from 18 background indoor air studies between 1990 and 2005. The most commonly detected VOCs in background indoor air were: benzene, toluene, ethylbenzene, and xylenes (BTEX); chloroform and carbon tetrachloride; and tetrachloroethylene (PCE), 1, 1, 1, trichloroethane (1,1,1,-TCA), and trichloroethylene (TCE). The data show large temporal and spatial variations in background air concentrations, in some cases spanning orders of magnitude.

Many of the studies included an inventory of consumer products in the home to account for possible VOC sources. Among the many background indoor air studies, the likely sources of measured VOCs are reported to be "consumer products" (e.g., cleaners, solvents, strippers, polish, adhesives, water repellants, lubricants, air fresheners, aerosols, mothballs, scented candles, insect repellants, plastic products); building materials (e.g., carpet, insulation, paint,

wood finishing products); combustion processes (e.g., smoking, cooking, home heating); fuels in attached garages; dry-cleaned clothing or draperies; municipal tap water; or occupant activities (e.g., craft hobbies) (USEPA 2011).

Neither the USEPA compilation (USEPA 2011) nor several federal and state vapor intrusion documents (USEPA 2002, ITRC 2007, NYSDOH 2006, MassDEP 2011) address the possible influence of sewer gas infiltration on indoor air concentrations. Some of these documents mention the potential for utility trenches and permeable trench backfill material to serve as preferential pathways for vapor intrusion, but do not reference the piping itself as a potential source for measured VOCs. Here we show that vapors emanating from a domestic sanitary sewer can be a source of PCE concentrations in indoor air, which is an especially timely contribution given the anticipated release of USEPA's finalized vapor intrusion guidance (Federal Register 2011).

The sewer gas infiltration documented herein should be accounted for in vapor intrusion investigations, either by considering it as a possible background source, or by updating the conceptual site model to include the potential for sewer gas to contaminate indoor air spaces. Inclusion of sewer gas pathways in the conceptual model would provide a new consideration for the PCE source-transport pathway-receptor configuration, where PCE transport into indoor air spaces could occur via a sewer network throughout an entire neighborhood, even in areas where soil and groundwater contamination are not known to exist. Whether or not sewer gas will enter the indoor space depends on plumbing features within a particular building—in particular, the nature of vapor traps and plumbing fixture seals.

The sewer gas to indoor air pathway was previously shown by others to be important during a chlorinated solvent vapor intrusion investigation in Denmark (Riis et al. 2010), as well as a petroleum vapor intrusion investigation in Pennsylvania (Hawkins 2008). Corroborating these findings, this article provides one of the first reports in the peer-reviewed literature suggesting gas from a municipal sewer contributed to PCE concentrations detected in indoor air during a vapor intrusion study. The results presented herein were collected as part of a field study aimed at calibrating a vapor intrusion model. The original intent of this research was not to investigate the contribution of vapors from sewer gas to the vapor intrusion pathway; however, during sampling indoor air in one of the field study homes, VOC vapors were detected at concentrations higher than anticipated and field personnel reported a strong sewer gas odor in the home. To investigate whether sewer gas may be contributing to the elevated VOC concentrations, the authors quickly responded by conducting targeted sampling of the home and a faulty sewer connection. The sampling was necessarily limited—the purpose was to identify the likely source of the VOC vapors in order to explain the elevated concentrations compared with other data from inside and outside the home. The objective of this paper was to provide rationale for practitioners and regulators to consider sewer gas as a potential source of PCE (and possibly other VOCs) during vapor intrusion investigations.

## Methods

The research site is located in a residential neighborhood in the greater Boston area, adjacent to a former chemical handling facility. For nearly 50 years this facility was the location for the transport of bulk PCE from trains to trucks and, ultimately, to drycleaners and other businesses. The decades of chemical handling at this property resulted in soil and groundwater contamination in the residential area adjacent to the site. As part of regulatory activities, one school and approximately 70 other properties were sampled to evaluate vapor intrusion risks. A number of vapor intrusion mitigation systems were installed at residences and the school. Testing is ongoing to determine whether additional homes and buildings will require mitigation systems (and associated long-term monitoring). These activities are being conducted by the Responsible Party and are overseen by the Massachusetts Department of Environmental Protection (MassDEP).

In this study, while characterizing vapor intrusion conditions in several homes from 2010 to 2011, elevated concentrations of chlorinated VOCs were detected in an indoor air sample collected on the first floor of a residence, but were not driven by basement concentrations. PCE was the only VOC that was detected at or above risk levels. The elevated concentrations were detected after the second round of sampling, at which time the homeowner had complained of a sewer-like odor on the first floor, leading the authors to consider the possibility of sewer gas infiltration. The same pattern (low basement concentrations and high first floor concentrations) was observed during the third round of sampling, including the odor, which was observed by the authors. Table 1 describes the sampling events, conditions, and dates of collection. Subsequent targeted sampling of the indoor air and sewer gas in this residence was conducted.

The first floor of the residence was unoccupied for all sampling events. Prior to the first sampling event, an inventory of potential indoor air contaminants such as consumer products was noted and no potential sources for the VOCs detected in the indoor air were identified. Beginning in the fourth round of our data collection, quarterly indoor air samples were collected using 6-L summa canisters deployed for 24 h in three different locations (one canister per location) within the residence: the basement; the first-floor living space; and the first-floor bathroom. Targeted sampling of the sewer pipe was conducted as follows: non-PCE-containing tape was used to seal the opening to the pipe, into which tubing was placed to collect a grab (10 min, 1 L) sample directly from the sewer pipe. Sampling tubing was sealed so as not to dilute the sample with ambient air.

Summa canisters were certified “clean” and the flow controllers were certified by the laboratory prior to field sampling. All data reported are from canisters with acceptable vacuums upon receipt at the laboratory. Laboratory sample preparation and analysis was conducted by a National Environmental Laboratory Accreditation Conference-certified laboratory (Columbia Analytical Services). Analyses were compliant with USEPA Method TO-15 (Volatile Organic Compounds in Air Analyzed by Gas Chromatography/Mass Spectrometry) and the laboratory's standard operating procedures that define requirements for calibration and acceptable results for quality control.

**Table 1**

**Description of Sampling Events and PCE Air Sampling Results**

Sampling Event	Date	PCE ( $\mu\text{g}/\text{m}^3$ )			Description	Sewer Odor
		1F	B	1FBR		
1	October 2010	1.2	1.5	NS	First-floor bathroom door was open during all sampling.	N
2	January 2011	37	3.3	NS	First-floor bathroom door was open during all sampling.	Y
3	April 2011	14	0.46	NS	First-floor bathroom door was open during all sampling.	Y
4	June 2011	0.88	0.39	2.1	First-floor bathroom door was closed during all sampling. Homeowner had removed the toilet. The sewer connection for the toilet was plugged with damp cloth. The space between the bathroom door and the floor was filled with clothes.	Slight
5	August 2011	0.64	0.36	190	First-floor bathroom door was closed during all sampling. The sewer connection for the toilet was open to indoor air. The space between the bathroom door and the floor was filled with clothes.	Y
6	October 5, 2011	NS	NS	62	Bathroom air sampled. The door to the bathroom was closed throughout sampling. The sewer connection for the toilet was open to indoor air. The space between the bathroom door and the floor was filled with clothes.	Y
7	October 6, 2011	NS	NS	2.6	Bathroom air sampled. The door to the bathroom was closed throughout sampling. The sewer connection for the toilet was sealed using a water bladder, polymer clay, and duct tape. In addition, drains and overflow holes in the sink and tub were sealed. The space between the bathroom door and the floor was filled with clothes.	N
8	October 7, 2011	NS	NS	58 <sup>1</sup>	Air from the sewer pipe was directly sampled. The sample tubing was sealed within the pipe, so ambient indoor air did not dilute the sample.	NA

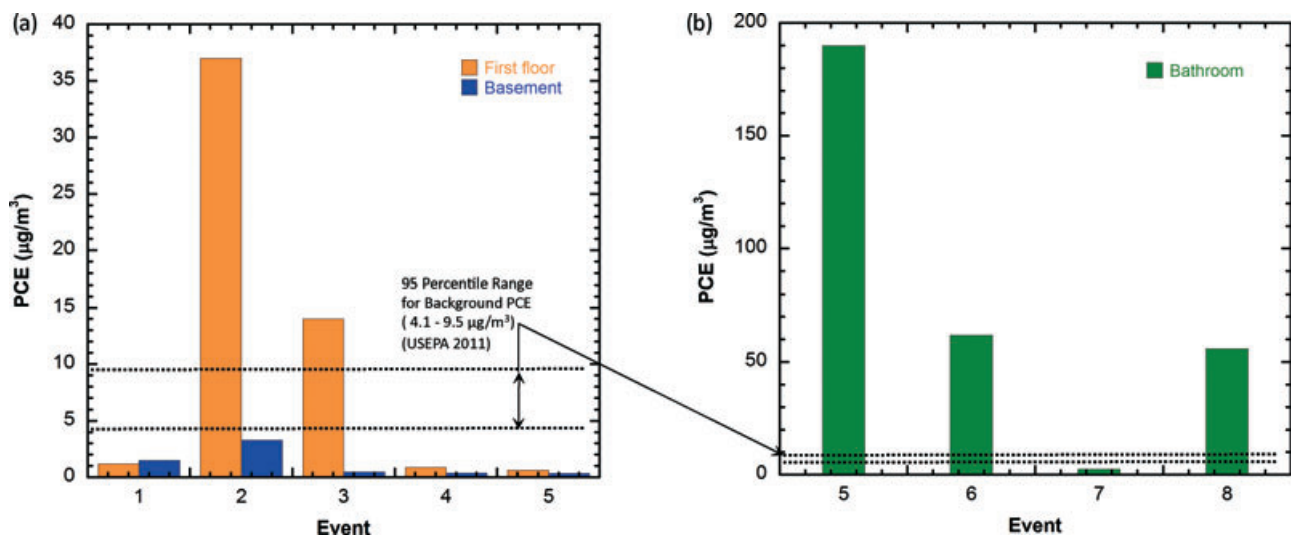
1F, first floor; B, basement; 1FBR, first-floor bathroom; NS, not sampled. All first-floor and basement samples were collected in general areas.

<sup>1</sup>The sample was collected directly from the sewer pipe, not from the bathroom ambient air.

parameters including; method blanks (all nondetects); laboratory control samples (all met 80 to 90% precision); surrogate recoveries (81 to 108% recoveries for bathroom samples and 79 to 111% for basement and nonbathroom, first-floor samples); and duplicate precision (relative percent different less than  $\pm 4\%$ ).

## Results

Table 1 and Figure 1 summarize the analytical results. Sewer gas transport into the home was suspected when unexplained increases in first-floor PCE concentrations corresponded with observations of indoor sewer gas odors (Table 1, sampling events 2, 3, 5, 6 and Figure 1a and 1b).



**Figure 1. PCE concentrations detected in air during sampling events. Notes:** Table 1 contains sample event descriptions. For Event 8, the air sample was collected directly from the sewer pipe itself, not the bathroom air. There are no US health-based standards for indoor air exposures to PCE; however, concentrations of 3  $\mu\text{g}/\text{m}^3$  (MassDEP 2011) and 4-40  $\mu\text{g}/\text{m}^3$  (USEPA 2011) correspond to benchmark cancer risks.

Targeted sampling of air in the bathroom in October 2011 (Table 1, sampling events 6 to 8) confirms that sewer gas contained elevated concentrations of PCE (Figure 1b). As previously mentioned, the results described herein were collected as an extension of a separate vapor intrusion research study. The sample number was necessarily limited because it was outside of the original research scope. While the limited number of samples prevented statistical analysis, the results strongly suggest that consideration of the sewer gas to indoor air pathway during vapor intrusion investigations is warranted.

During the second round of sampling (Event 2), elevated VOC concentrations were detected on the first floor. Given that PCE was the contaminant of concern at the site, and the relatively large concentrations we measured, we focus our reporting on PCE. Other VOCs fluctuated during the sampling events (data not shown), but PCE concentrations varied dramatically (orders of magnitude) and were frequently detected above the 95th percentile range for indoor air background concentrations calculated by USEPA (2011). As shown in Figure 1a (and Table 1), the PCE concentration was one order of magnitude greater during Event 2 than in the previous sampling event. In addition, the PCE concentration was substantially greater on the first floor than in the basement, which suggested the presence of an in-home source. Event 2 was also the first instance that a strong sewer gas odor was noted during the sampling. In accordance with the participant engagement and data-sharing plan for the research study, the property owner was informed of the sampling results, the unexpected high levels on the first floor, and the potential risks of exposure to the VOCs.

In April 2011, a third round of sampling was conducted (Event 3). A strong sewer gas smell emanating from the bathroom was noted on the first floor and analytical results again indicated a source on the first floor. The PCE concentration was lower than the previous sampling round; however, PCE concentrations were on the same order of magnitude and still were considerably higher than the first sampling round when no sewer gas odor was noted (Figure 1a and Table 1).

During the June 2011 sampling event (Event 4), an indoor air sample was collected from the first-floor bathroom (door and windows closed), while a separate indoor air sample was collected from the standard sampling location on the first floor. Between the April and June sampling events, the property owner had removed the toilet and plugged the open sewer pipe with a damp cloth in an attempt to address the odor issue. During sampling, a fainter sewer odor was noted, as the damp cloth plugging the sewer pipe appeared to be limiting sewer gas infiltration. Figure 1a and Table 1 show PCE concentrations returned to lower levels, although the first-floor sample remained higher than the basement sample.

The August 2011 sampling event (Event 5) was conducted to assess whether the sewer pipe was the source of the elevated concentrations. During this sampling event, the pipe was unplugged and the bathroom door remained closed. The bathroom had a strong sewer odor; however, the sewer gas odor in the rest of the first floor was slight. The sample from the first floor, taken coincidentally outside

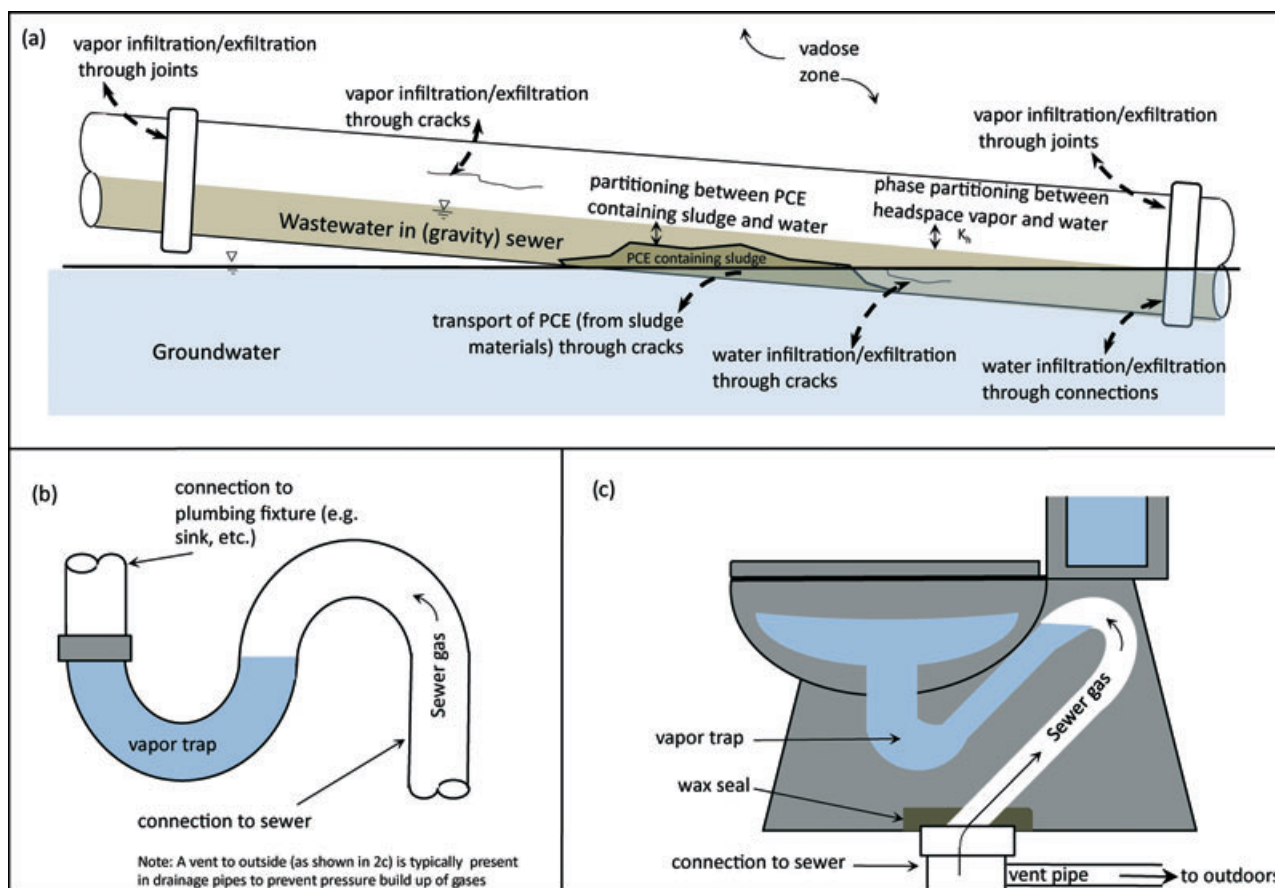
the bathroom, was two orders of magnitude less than the PCE concentration detected inside of the bathroom. Upper percentile concentrations of PCE and TCE in residences in the absence of contribution from a known vapor intrusion pathway are measured in the range of 0.0014 to 0.0041 mg/m<sup>3</sup> and for TCE from 0.0029 to 0.0008 mg/m<sup>3</sup> (MassDEP 2008). The elevated concentrations (Figure 1a and 1b and Table 1) strongly suggested the sewer as a source for PCE vapor.

To further confirm whether sewer gas was the source of elevated PCE concentrations, targeted sampling of the bathroom and the sewer pipe was conducted in October 2011 as outlined in Table 1. Measured concentrations of PCE are presented in Figure 1b. The results clearly indicate the sewer pipe is a primary source of PCE concentrations to bathroom air. In fact, as shown in Figure 1b, the concentration of the bathroom air when the sewer pipe was open (Event 6) was nearly identical to the PCE concentration within the sewer pipe itself (Event 8).

## Discussion

Sewer gas is a generic name for a complex mixture of gases and airborne agents that result from the natural process of the decomposition of organic materials in sewage. Typically, the agents of human health concern are sulfide (H<sub>2</sub>S), ammonia (NH<sub>3</sub>), methane (CH<sub>4</sub>), and to a lesser extent, carbon dioxide (CO<sub>2</sub>). Public health risks due to these exposures are focused on acute toxicity and physical hazards resulting from explosions and, rarely, asphyxiations (ATSDR 2004). Massachusetts regulations regarding sewer gas focus on plumbing and housing code violations in addition to nuisance and odor (MGL Ch.11, 105CMR410). Human recognition of sewer gas depends on an individual's ability to detect the odor of hydrogen sulfide. The estimated odor threshold of H<sub>2</sub>S is in the range of 0.004 to 0.03 mg/m<sup>3</sup>, although adverse health effects of H<sub>2</sub>S occur at a much higher concentration in the indoor space (USEPA 2003). This is in contrast to low concentrations identified for protection from health effects associated with indoor air exposures to many chlorinated solvents including PCE and TCE. While there are no U.S. health-based standards for indoor air exposures to PCE, concentrations of 3 µg/m<sup>3</sup> (MassDEP 2011) and 4 to 40 µg/m<sup>3</sup> (USEPA 2011) correspond to benchmark cancer risks. These concentrations are based on long-term residential exposures and are within the range of typical indoor air concentrations. Odor thresholds are much higher for these chemicals, indicating the utility of using sewer-gas odors as an indicator of the possible presence of VOCs in the sewer vapors. However, if there is no sewer gas smell indoors, then it cannot be concluded that the sewer pathway is not important for VOCs. Whether VOCs or the more typical sewer gas chemicals, the critical exposure pathway is inhalation of vapor derived from bathroom plumbing fixtures.

Concentrations of PCE in the bathroom ranged from 2.1 to 190 µg/m<sup>3</sup>, which exceed the typical indoor air concentrations by orders of magnitude (MassDEP 2008; USEPA 2011) and present human health risks classified as "Imminent Hazard" conditions. Strong sewer gas odors



**Figure 2. Pathways for VOCs in sewers and plumbing traps.**

were observed when PCE concentrations were measured at  $37 \mu\text{g}/\text{m}^3$  in January 2011 (Event 2) and at  $14 \mu\text{g}/\text{m}^3$  in April 2011 (Event 3), but were much less noticeable in June 2011 (Event 4) when concentrations were measured at  $0.88$  to  $2.1 \mu\text{g}/\text{m}^3$ , which were concentrations not indicative of conditions requiring immediate attention. However, using typical residential exposure conditions of 24 h/d for 30 years, data demonstrate that the concentrations of PCE in the bathroom were high enough to elevate the concentrations on the first floor (outside the bathroom) to conditions that pose an unacceptable human health risk.

Figure 2 shows various explanations for the presence of PCE vapors in a sewer line. Several previous studies have reported a history of dry-cleaning-related operations discharging contact water, as well as free-phase PCE to municipal sewers (e.g., State Coalition for Remediation of Drycleaner Sites 2010). Discharge of PCE-containing water was common during the operational times for the facility at the research site and could have resulted in PCE-containing sludge to exist within the sewer system. If PCE-laden material is present within a sewer line, it can result in PCE vapors in the sewer headspace, and it can also result in contamination surrounding the sewer line. Vroblesky et al. (2011) documented the effect of leaky sewers allowing PCE to contaminate soils adjacent to sewer lines.

Aside from PCE-containing sludge materials serving as a source of PCE vapors, contaminated vapors in the vadose zone can enter the sewer through deteriorated joints and/or

cracks in the piping. In addition, if the sewer line is located below the groundwater table, contaminated groundwater could also enter the sewer through deteriorated joints and/or cracks. Any volatile chemicals present in the liquid within the sewer water could then partition into the vapor phase under appropriate environmental conditions. It should be noted that vapor phase partitioning would include chemicals present in the wastewater itself and/or from the chemicals present in contaminated groundwater that may infiltrate into the sewer and mix with the wastewater already within the sewer.

Once VOCs are present in the sewer, they can potentially enter an indoor space by many routes, including plumbing fixtures as documented here. Figure 2b and 2c show how the vapors within the sewer are typically contained within the sewer pipe via water traps associated with plumbing fixtures and drains. The traps prevent vapors from directly venting to the indoor air. Therefore, in buildings where plumbing is appropriately installed and maintained, sewer gas infiltration is unlikely. However, if traps and/or drains become dry, or if the wax that seals the connection between the toilet and the sewer is not properly working, sewer gas vapors may enter the indoor air space.

This study did not investigate where the chemicals within the sewer vapor originated. Arguably, any of the pathways shown in Figure 2 may have been occurring. There are many reported instances of sewer gas odors posing a nuisance and codes regulating "sewer gas" as nuisance

**Table 2**  
**Daily Discharge Limits to POTWs Within MWRA Jurisdiction**

Constituent	Max Daily Limit (mg/L)	Henry's Law Constant <sup>1</sup> (—)	Gas-Phase Equilibrium (µg/m <sup>3</sup> )	Bkd Conc. <sup>2</sup> 75 Percentile (µg/m <sup>3</sup> )	Bkd Conc. <sup>2</sup> 95 Percentile (µg/m <sup>3</sup> )
Benzene	0.3	0.145	43,500	1.9 to 7.0	9.9 to 29
Vinyl chloride	0.02	0.862	17,240	<RL <sup>3</sup>	<RL <sup>3</sup> to 0.09
Toxic organics (each)	1				
Relevant compounds for vapor intrusion					
TCE	—	0.263	263,000	<RL <sup>3</sup> to 1.2	0.56 to 3.3
PCE	—	0.441	441,000	<RL <sup>3</sup> to 4.1	4.1 to 9.5
1,1,1-TCA	—	0.457	457,000	<RL <sup>3</sup> to 7	3.4 to 28
Carbon tetrachloride	—	0.810	810,000	<RL <sup>3</sup> to 0.72	<RL <sup>3</sup> to 1.1
Ethylbenzene	—	0.183	183,000	2 to 5.6	12 to 17
Toluene	—	0.163	163,000	12 to 41	79 to 144
Xylenes <sup>4</sup>	—	0.177	177,000	2.4 to 21	13 to 20
Total toxic organics	5	NA	NA	NA	NA

1. OSWER method (<http://www.epa.gov/athens/learn2model/part-two/onsite/esthenry.html>).

2. Percentile background indoor air concentration range based on data compiled by USEPA 2011.

3. Reporting limit (RL) range (µg/m<sup>3</sup>):

Vinyl chloride: 0.01 to 0.25

TCE: 0.02 to 2.7

PCE: 0.03 to 3.4

Carbon Tetrachloride: 0.15 to 1.3

4. Henry's Law constant reported for xylenes-p. IA BG percentiles reported for m/p/o.

(e.g., MGL Ch.111, 122), which substantiates the claim that sewer vapors do enter indoor air spaces. For the research described herein, the property owner noted that the toilet did not appear to be properly attached to the sewer pipe—either a faulty wax seal or damage to the sewer pipe itself may have been allowing sewer gas to enter the indoor space.

Fairly high concentrations of PCE contamination in the soil and groundwater are known to exist near the site of the indoor air sampling. Given that the sewer pipes in the area are decades old, vapors within the vadose zone may have entered the sewer line through deteriorated joints and/or cracks. It is equally plausible that the wastewater within the sewer contained elevated concentrations of PCE due to potential infiltration of contaminated groundwater, and/or via permitted discharges to the publically operated treatment works (POTW).

Many of the chemicals regulated by the Clean Water Act for discharge into POTWs are also chemicals of concern for vapor intrusion. Federal regulations restrict industrial pollutants from being discharged to POTWs and POTWs can impose more stringent limitations of their own. In addition to restrictions, federal regulations also address pretreatment requirements for specific industries (which are known as “categorical pretreatment standards”). Specific pretreatment requirements exist for various chemicals, but in general many vapor intrusion chemicals fall into the category of total toxic organics for which the discharge criteria vary depending on industry and discharge volumes. Based on the current regulations, many industrial discharges have maximum daily discharge criteria of 2.13 to 4.57 mg/L per 40 Code for Federal Regulations, Part 400.

On a local level, the discharge criteria for total toxic organics can vary greatly. For instance, the discharge limits

set forth by the Massachusetts Water Resources Authority (MWRA) are provided in Table 2. MWRA oversees sewer discharges in the greater Boston area. Henry's Law constants, the calculated equilibrium gas-phase concentrations, and background indoor air concentrations summarized by USEPA (2011) are also included in Table 2, demonstrating that discharges to sewers that are in compliance with discharge limits could result in sewer gas concentrations that are significantly higher than background concentrations of VOCs in indoor air. However, sewer gas concentrations of VOCs do not directly correlate with background indoor air concentrations because not all sewers will carry wastewater that is at the upper limit of the allowable concentrations and, more importantly, sewer gas infiltration is routinely controlled by the installation of “traps” (Figure 2). Regardless of the exact source of the sewer vapors, the data presented in Table 1 and Figure 1 clearly indicate vapors within the sewer pipe were present at concentrations high enough to influence indoor air concentrations.

## Implications

VOC vapor intrusion investigations operate within the litigiously complex arena of hazardous waste sites, where establishing a link between the exposure and a particular hazardous waste site is required. Of course, this link does not change the health risk, it merely changes who is responsible—a homeowner (in the case of in-home concentrations) or the hazardous waste site Responsible Party (in the case of VOC vapor intrusion). If indoor air contamination is found to be due to vapor intrusion, typically a Responsible Party is required to mitigate the exposure. However, if the indoor air concentrations are at or below background, than

there are few, if any, legal requirements to reduce the indoor air concentrations to risk-based targets.

Some states have developed their own vapor intrusion guidance documents, but many rely on draft guidance published by the U.S. Environmental Protection Agency in 2001 with amendments in 2002 (USEPA 2002). USEPA is currently working to finalize its vapor intrusion guidance with now past deadline of November 2012 (Federal Register 2011). In the absence of finalized federal guidance, the Interstate Technology and Regulatory Council (ITRC), whose membership includes regulators in 50 states, released a document to assist investigators in the evaluation of vapor intrusion pathways and the characterization of risks (2007). USEPA has since produced several technical guidance documents to provide a better fundamental understating of vapor intrusion, incorporating nearly a decade of new science (USEPA 2010, 2011, 2012, etc.).

To better characterize the vapor intrusion pathway, the soon-to-be-finalized USEPA's vapor intrusion guidance will incorporate a "multiple lines of evidence approach" (Federal Register 2011). This approach is consistent with many existing vapor intrusion guidance documents (ITRC 2007) that require vapor intrusion investigations include the collection of many different types of data (e.g., indoor air samples from affected buildings, soil gas samples around and/or beneath the building of concern, groundwater samples from nearby monitoring wells, and even modeling). The data presented herein suggest sewer gas as a source of VOCs in indoor air should also be considered, either as part of the conceptual site model, or when evaluating possible background concentrations. Under the "multiple lines of evidence approach," if sewer odors are observed during a vapor intrusion investigation, targeted sampling of potential sewer sources should be conducted. Aside from evaluating odors, site professionals should also consider collecting sewer gas samples from sewer cleanouts and/or the sewer main itself, to evaluate the potential for sewer gas to contribute to VOCs indoor air. In evaluating these data within the context of the overall site risk assessment process, interaction with agencies, such as POTWs, local inspectional services, and health departments that have limited experience with vapor intrusion may be required and gaps in regulatory authority may exist.

Risk-based regulatory frameworks frequently guide programmatic criteria and decisions. Due to the multitude of organizations involved in oversight and regulation of human exposures to VOCs in the indoor space, it is not surprising that, despite overlapping authorities, gaps in the system do not adequately address sewer-line sources of VOCs. Specifically, multiple authorities govern wastewater discharge (state agencies and POTWs, USEPA), groundwater contamination and cleanup (e.g., MassDEP), sewer and pipe maintenance (state, local and uniform plumbing codes, local DPW, etc.) and public health considerations (state sanitary and public health agencies). In part because of the multiple management silos, risk management focus and criteria are segregated, with little ability to integrate across and within local, state, and federal authorities.

The situation and data presented in this article are the first to document a complete pathway between PCE-containing

sewer pipes and potential human exposures to PCE in the indoor air. While our study focused on PCE, our findings may have implications for other VOCs present in sewers. Many organizations regulate the structures and flow of material in wastewater sanitary sewers; however, none of the regulatory frameworks identify potential public health exposures or health risks of inhalation of VOCs from sewers via plumbing fixtures in the indoor environment. Better communication between regulators and integrated oversight is needed. Public health officials should be taught to associate sewer gas with substances other than organic decomposition and might use the nose as an inexpensive detector of potential release of VOCs into the indoor space. Sewer gas odors can be indicative of a completed sewer-to-indoor air pathway; however absence of odor does not confirm that pathway does not exist. Site professionals should conduct targeting sampling of sewer connections, cleanouts and piping to evaluate the sewer-to-indoor air pathway.

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